Searching for heavy neutral leptons using τ decays at *BABAR*

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BABAR

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The 13th International Workshop on e^+e^- collisions from Phi to Psi
Fudan University, Shanghai, China. August 15 - 19, 2022

Standard Model

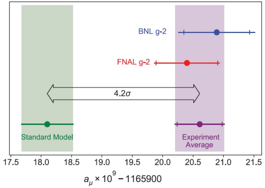
Standard Model extremely successful

very large number of high precision tests – almost all passed with flying colours

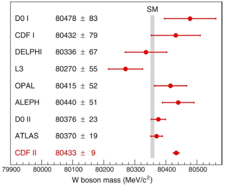
yet some intriguing discrepancies:

SM anomalies

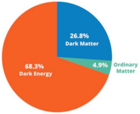
anomalous muon magnetic moment



W mass

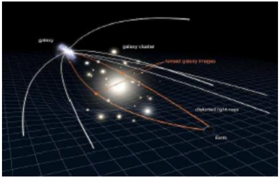


Astrophysical evidence for Dark matter

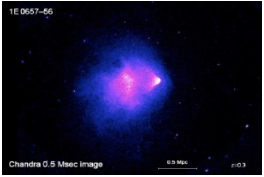


$> 6\times$ **more abundant than visible matter**

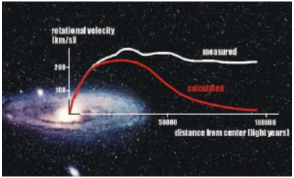
Gravitational lensing



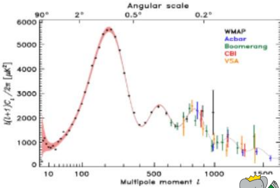
Bullet Cluster



Galactic rotation



CMB

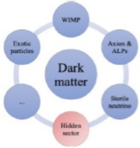


Physics beyond Standard Model: neutrino portal

Dark matter firmly established – "SM anomalies" tantalizing
search for new physics incorporating new terms in Lagrangian

Dark Matter not seen in particle physics experiments

SM can not explain DM $\Rightarrow$ Extending the SM to include DM



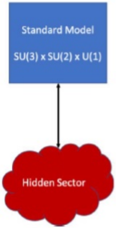
$$\mathcal{L} \supset \begin{cases} -\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}, & \text{vector portal} \\ (\mu\phi + \lambda\phi^2) H^\dagger H, & \text{Higgs portal} \\ y_n L H N, & \text{neutrino portal} \\ \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}, & \text{axion portal.} \end{cases}$$

A' kinetic mixing with γ, Z

Dark Higgs (mixes with SM Higgs)

Sterile neutrino

Axion, coupling to DM



This talk focused on the "Neutrino portal"

BABAR is exploring also LFV, dark photon and axion portals
(see talks by N. Tasneem , B. Echenard, and S. Ngan Nguyen)

Neutrino Oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino oscillation firmly established:

$\boxed{\text{neutrinos have mass}}$

PMNS matrix parametrization:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} P$$

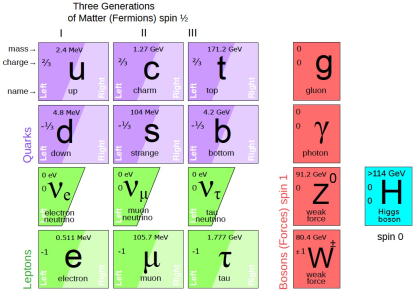
Experiments at accelerators, reactors and underground facilities are providing more and more precise determinations of

$\boxed{\text{PMNS matrix elements}}$ and $\boxed{\Delta m^2_{21} \text{ and } \Delta m^2_{32}}$

but a number of questions unanswered

- Neutrino mass is small: what are the origins of this mass?
- Why is neutrino mixing so different from quark mixing?
- CP violation?
- Nature of neutrinos?

Dirac /Majorana neutrinos?



in "standard" Standard model
massless neutrinos

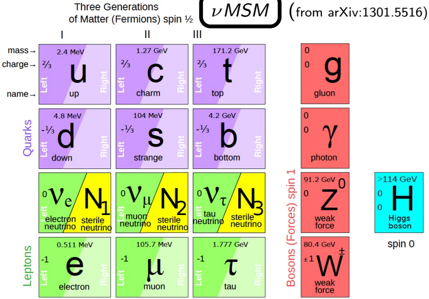
$\Longrightarrow$ no mixing

masses and mass hierarchy much different from charged leptons

oscillations via Higgs coupling of LH and RH fermions $\Longrightarrow$ Dirac mass

νs have 0 charge: can also oscillate coupling to $\bar{\nu}$s $\Longrightarrow$ Majorana mass

νMSM (from arXiv:1301.5516)



Appealing hypothesis: light Dirac neutrinos and heavy Majorana neutrinos of opposite chirality (see-saw)

Heavy Neutral Leptons?

Heavy Neutral leptons are additional neutrino states which have (some) mass but no weak hyper-charge, electric charge, weak isospin and color charge.

HNLs proposed by many BSM models to help explaining
Neutrino Oscillations, Baryon Asymmetry, Dark Matter

If neutrinos get their mass from Higgs, Yukawa couplings must be exceedingly small
Not so in see saw models with 5-dim operator and additional Majorana neutrinos
PRD 23, 165 (1981), https://doi.org/10.3389/fphy.2018.00040

Sterile neutrinos could also help explaining
Reactor Anti-neutrino anomaly PRD 83, 073006 (2011),
Gallium anomaly PRC 80, 015807 (2009)
Accelerator anomalies: LSND PRD 64, 112007 (2001),
MiniBooNE PRL 110, 161801 (2013)

Predicted mass ranges for HNL

Different models may introduce HNL in a broad mass range:

- $m_4 \approx \mathcal{O}(\mathrm{eV}/c^2)$ address the so-called "oscillation anomalies"
- $m_4 \approx \mathcal{O}(\mathrm{keV}/c^2)$ provide warm dark matter candidate.
- $m_4 \approx \mathcal{O}(\mathrm{GeV}/c^2)$ explain deviations in SM decays.
- $m_4 \approx \mathcal{O}(\mathrm{TeV}/c^2)$ explain Baryonic Asymmetry via low-scale scenarios of leptogenesis without conflict with other cosmological observations.

e.g.: νMSM model PLB 620, 17 (2005) introduces three right-handed singlet HNLs:

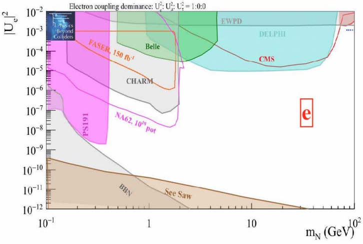
- Two GeV/c^2-scale particles to solve origin and smallness of SM neutrino mass with see saw mechanism
- a third HNL keV/c^2-scale dark matter candidate, that also provides leptogenesis (Majorana mass term)

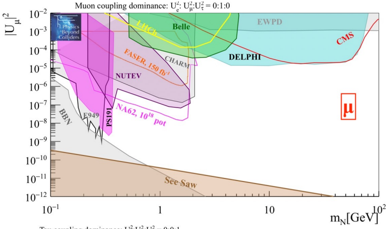
different methods/techniques needed to test such a variety of models

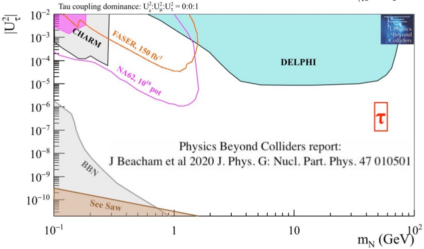
HNL in the MeV/c^2- GeV/c^2 scale can be searched for at existing accelerator experiments.

Extended PMNS Matrix and current limits on $|U_{\ell\,4}|^2$

with one additional neutrino: $$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_{\rm L}\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3} & U_{e4}\\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4}\\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4}\\ U_{\rm L1} & U_{\rm L2} & U_{\rm L3} & U_{\rm L4}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{pmatrix}$$







limits on $|U_{\ell\,n}|^2$:
current (filled); projected (solid)

less stringent limits on $|U_{\tau\,4}|^2$ $\Longrightarrow$ can be improved by studying τ decays

Searching for HNLs at *BABAR*

arXiv:2207.09575

NEW

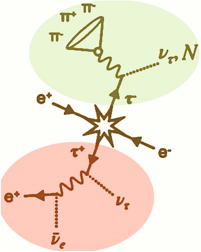
$$\sigma(e^+e^- \to \tau^+\tau^-) = 0.919 \pm 0.003 \text{ nb} \qquad \mathcal{L}_{int} = 424 \text{ fb}^{-1}$$

$$N_{\tau^+\tau^-} = 4.6 \times 10^8 \text{ collected}$$

Exploit the peculiar topology provided by the boost in E_{CM} to select τ pairs
charged daughters from each τ in one hemisphere

Method proposed in PRD 91, 053006 (2015),
inspired by ALEPH, EPJ 1137C 2, 395 (1998)

The study of $\tau^- \to \pi^-\pi^-\pi^+\nu$ decay
allows to access $100 < m_4 < 1360 \text{ MeV}/c^2$



model independent: rely only on kinematics

3h dynamics $\Longleftrightarrow$ neutrino mass

Select clean samples with $\tau^+ \to e^+\nu\overline{\nu}$ (tag) and
$\tau^- \to \pi^-\pi^-\pi^+\nu$ (3h)

Outline of the method

arXiv:2207.09575

NEW

$$\tau^- \to \pi^-\pi^-\pi^+\nu_x$$

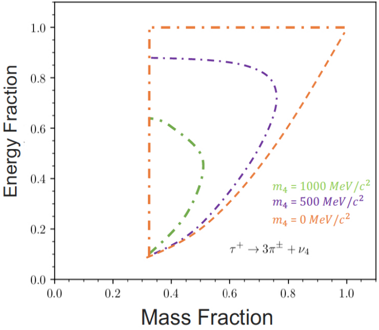
Mass of the missing neutrino (m_4) determines the 2D distribution of hadronic energy E_h vs invariant mass m_h

In the center of mass: $E_\tau = \frac{1}{2}E_{cm}$

$$3m_{\pi^\pm} < m_h < m_\tau - m_4$$

$$E_\tau - \sqrt{m_4^2 + q_+^2} < E_h < E_\tau - \sqrt{m_4^2 + q_-^2}$$

$$q_\pm = \frac{m_\tau}{2}\left(\frac{m_h^2 - m_\tau^2 - m_4^2}{m_\tau^2}\right)\sqrt{\frac{E_\tau^2}{m_\tau^2} - 1} \pm \frac{E_\tau}{2}\sqrt{\left(1 - \frac{(m_h+m_4)^2}{m_\tau^2}\right)\left(1 - \frac{(m_h-m_4)^2}{m_\tau^2}\right)}$$



2D distribution as sum of ν_τ (SM,m=0) component and a HNL component

$$\left.\frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\right|_{\text{Total}} = |U_{\tau 4}|^2 \left.\frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\right|_{\text{HNL}} + (1 - |U_{\tau 4}|^2)\left.\frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\right|_{\text{SM}}$$

Background and signal simulation

arXiv:2207.09575

NEW

Event sample has contribution from a number of sources

$\Longrightarrow$ MC simulations

Detector response modelled using GEANT4

event generator specific to each source

non-τ backgrounds

- $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ EvtGen
- $e^+e^- \to c\overline{c}$ JETSET
- $e^+e^- \to \mu^+\mu^-(\gamma)$ KK2F

SM 3-prong decay $\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$ TAUOLA, KK2F

other SM τ decays accidentally reconstructed as 3h TAUOLA, KK2F

all SM neutrinos are assumed to have m=0

HNL 3-prong decay $\tau^- \to \pi^+\pi^-\pi^-\nu_X$ – large missing mass TAUOLA, KK2F

parameters modified to attribute large mass to ν

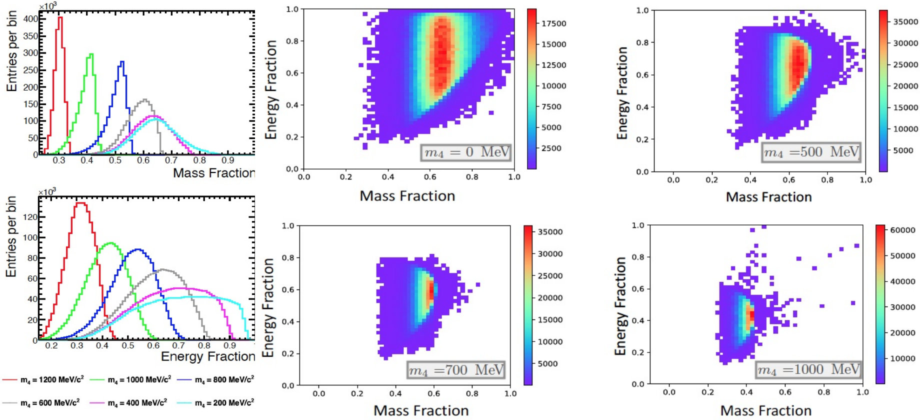
Signal MC samples

arXiv:2207.09575

NEW

1D and 2D projections for signal HNL 3-prong decays $\tau^- \to \pi^+\pi^-\pi^-\nu_X$

visible change in the expected 2D template as a function of m_4



largest sensitivity for large m_4

Fit model

arXiv:2207.09575

NEW

Minimize likelihood for the observed # of events in each bin to extract $|U_{\tau 4}|^2$

$$\mathcal{L} = \prod_{ij} f(n_{ij}; n_{\text{obs}}, \vec{\theta}) = \prod_{ij} \frac{(\nu_{\text{HNL}} + \nu_{\tau-\text{SM}} + \nu_{\text{BKG}})_{ij}^{(n_{\text{obs}})_{ij}} e^{-(\nu_{\text{HNL}} + \nu_{\text{BKG}} + \nu_{\tau-\text{SM}})_{ij}}}{(n_{\text{obs}})_{ij}!} \times \prod_k f(\theta_k, \tilde{\theta}_k)$$

as a sum of the expected number of events in each bin for

- HNL 3-prong decays $\tau^- \to \pi^+\pi^-\pi^-\nu_X$:

  $$\hat{\nu}_{\text{HNL},ij} = n^{\text{reco}}_{\text{HNL},ij} = N_{\tau,\text{gen}} \cdot (|U_{\tau 4}|^2) \cdot p_{\text{HNL},ij}$$

- SM 3-prong decays $\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$:

  $$\hat{\nu}_{\tau-\text{SM},ij} = n^{\text{reco}}_{\tau-SM,ij} = N_{\tau,\text{gen}} \cdot (1 - |U_{\tau 4}|^2) \cdot p_{\tau-SM,ij}$$

- other sources

  $$\hat{\nu}_{\text{BKG},ij} = n^{\text{reco}}_{BKG,ij} = n^{\text{reco}}_{\tau-\text{other},ij} + n^{\text{reco}}_{\text{non}-\tau,ij}$$

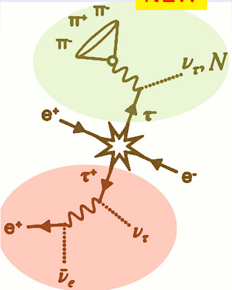
$p_{i,j}$ accounts for acceptance$\times$efficiency$\times$Ph.Sp.

Upper limits (Wick's theorem): $q = -2\ln\left(\frac{\mathcal{L}_{H_0}(|U_{\tau 4}|^2_0; \hat{\hat{\theta}}_0, \text{data})}{\mathcal{L}_{H_1}(|\hat{U}_{\tau 4}|^2; \hat{\theta}, \text{data})}\right) = -2\ln(\Delta\mathcal{L})$

Event selection

arXiv:2207.09575

NEW



Selection optimized for

$\boxed{\tau^+ \to e^+\nu\overline{\nu}}$ and $\boxed{\tau^+ \to \mu^+\nu\overline{\nu}}$ (tag)

and $\boxed{\tau^- \to \pi^-\pi^-\pi^+\nu}$ (3h)

Cut	Purpose
Number of tracks	Ensure 1+3 prong topology
Total charge on all 4 charged tracks is 0	Charge conservation
$p_{CM}^{miss} > 0.9\%\sqrt{s}$	Suppresses non-tau backgrounds
All tracks: $p_{trans} > 250\text{MeV/c}$	To reach DIRC[1]
All tracks: $-0.76 < \cos(\theta) < 0.9$	Acceptance of DIRC[1]
1 prong: $\frac{2p}{E} < 0.9\%$	Consistent with tau decay
PID Requirements	Uses Electron and Muon ID algorithms

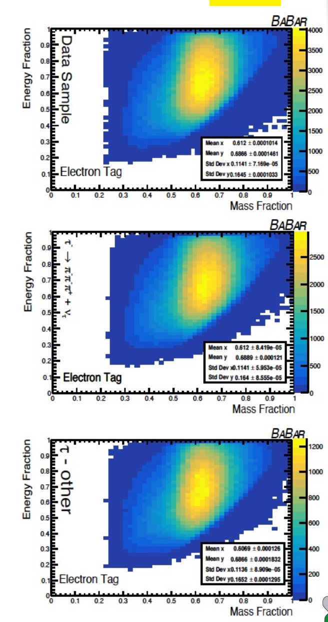
2D plots: examples (data and MC)

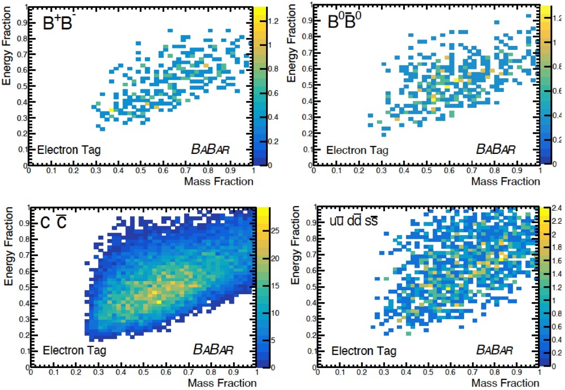
arXiv:2207.09575

NEW

electron-tag τ^+ and τ^- samples studied separately for consistency

(similarly for muon-tag)





Systematic uncertainties: normalization

arXiv:2207.09575

NEW

Uncertainty	Yield Change (±)
Luminosity	0.44%
$\sigma(ee \to \tau\tau)$	0.31%
Branching Fractions (1 prong)	e: 0.22%
	μ: 0.22%
Branching Fractions (3 prong)	3π: 0.57%
PID Efficiency	e: 2%
	μ: 1%
	π: 3%
Bhabha Contamination	0.2%
$q\bar{q}$ Contamination (data)	0.1%
Tracking Efficiency	negligible
Detector Modeling	negligible
Beam Energy	negligible
Tau Mass	negligible

NEW

Systematic uncertainties: 2D shape templates

The $\tau \to 3\pi\,\nu$ decay is dominated by $\tau \to a_1\,\nu$

The shape of the 3h template depends on the a_1 mass and width parameters

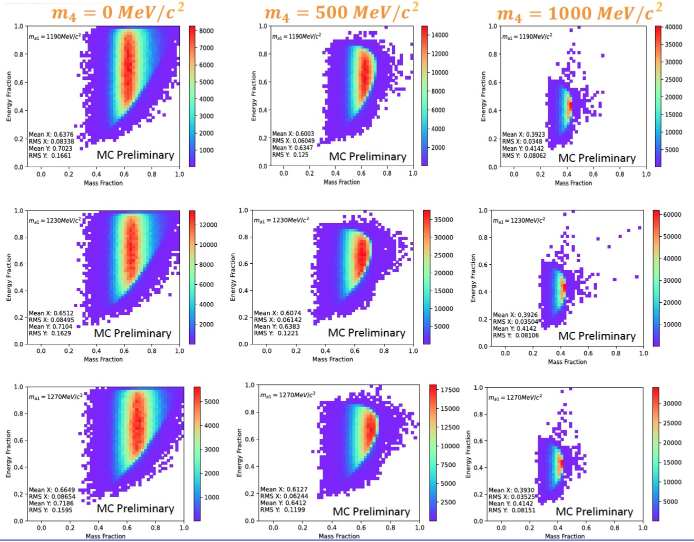
$\Longrightarrow$ systematic based on uncertainties from PDG

$m(a_1) =$

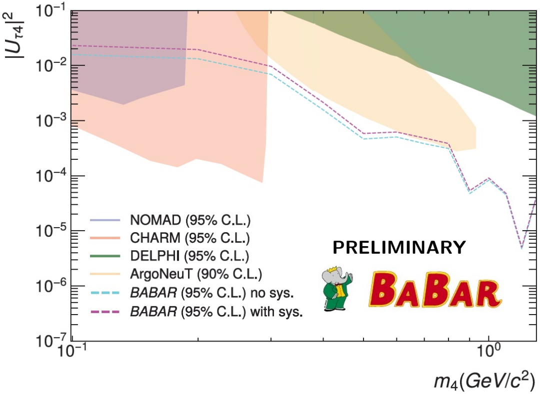
1190 MeV/c^2

1230 MeV/c^2

1270 MeV/c^2



Limits on $|U_{\tau 4}|^2$ vs HNL mass



Mass [MeV/c^2]	No Sys.	With Sys.
100	1.58×10^{-2}	2.31×10^{-2}
200	1.33×10^{-2}	1.95×10^{-2}
300	6.91×10^{-3}	9.67×10^{-3}
400	1.57×10^{-3}	2.14×10^{-3}
500	4.65×10^{-4}	5.85×10^{-4}
600	5.06×10^{-4}	6.22×10^{-4}
700	3.82×10^{-4}	4.85×10^{-4}
800	3.12×10^{-4}	3.85×10^{-4}
900	4.70×10^{-5}	5.38×10^{-5}
1000	8.34×10^{-5}	9.11×10^{-5}
1100	4.49×10^{-5}	4.78×10^{-5}
1200	4.70×10^{-6}	5.04×10^{-6}
1300	3.85×10^{-5}	4.09×10^{-5}

arXiv:2207.09575 (submitted to PRD)

Summary and outlook

HNLs offer ways of explaining several observational phenomena.

The possible masses of the HNLs is model dependent and can range from eV/c^2 up to very heavy masses.

In the last few years several new results have been published including results from collider-based experiments and neutrino experiments.

arXiv:2207.09575 NEW

A new technique has been adopted by *BABAR* to search for HNLs obtaining new preliminary upper limits on $|U_{\tau 4}|^2$ between 100 and 1300 MeV/c^2

currently the most stringent between 300 and 1300 MeV/c^2

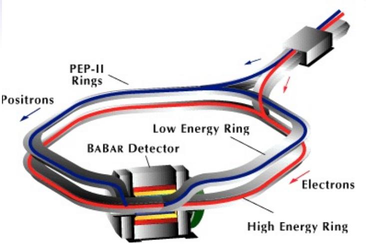
submitted to PRD

BABAR result is competitive with expected limits from planned experiments in the next decade

Improvements could be obtained by the same technique by Belle-II

BACKUP

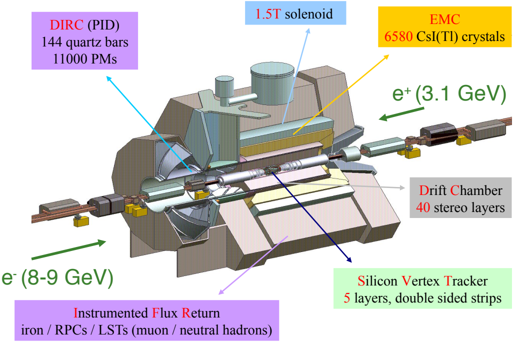
The *BABAR* experiment



PEP-II asymmetric e^+e^- collider operating at center of mass energies near the $\Upsilon(4S)$ (for most of the time)

$$\sqrt{s} = 10.58\,\mathrm{GeV}/c^2$$

General-purpose detector



Asymmetric detector:

$$-0.9 < \cos\theta^* < 0.85$$

wrt electron beam

excellent performance:

- vertexing
- tracking
- PID
- calorimeter

Data samples